

Solar neutrino interactions with liquid scintillators used for double beta-decay experiments

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Abstract. Solar neutrinos interact within double-beta-decay (DBD) detectors and hence will contribute to backgrounds (BG) for DBD experiments. Background contributions due to solar neutrinos are evaluated for their interactions with atomic electrons and nuclei in liquid scintillation detectors used for DBD experiments. They are shown to be serious backgrounds for high-sensitivity DBD experiments to search for the Majorana neutrino masses in the inverted and normal hierarchy regions.

Key words: solar- ν interaction, double beta decay, liquid scintillation detector, neutrino mass, solar- ν backgrounds.

1. Introduction

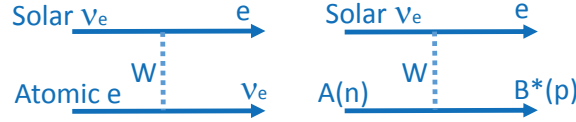
Neutrino-less double beta decays ($0\nu\beta\beta$) are crucial for studies of the neutrino (ν) properties and especially the Majorana mass character of the neutrino. With the given current knowledge from neutrino oscillation experiments, the typical mass regions to be explored are about 45-15 meV and 4-1.5 meV in cases of the inverted hierarchy (IH) and normal hierarchy (NH) mass spectra, respectively. Since the $0\nu\beta\beta$ half-lives expected for these regions are well above 10^{26-27} years, the $0\nu\beta\beta$ rates are so low that large scale detectors have to be used. The amount of double-beta-decay (DBD) isotopes for such experiments are multi tons and multi 100 tons for IH and NH masses, also depending on the nuclear matrix element and the phase space volume. Background rates, thus, have to be necessarily as low as an order of or less than 1 per year (y) per ton (t) in the region of interest (ROI) at the Q -value in the sum energy spectrum of the two β rays. DBD studies and ν masses are discussed in recent reviews and their references [1, 2, 3, 4].

The solar- ν s are omnipresent and cannot be shielded, and thus their charged current (CC) and neutral current (NC) interactions are potential background (BG) sources for high sensitivity DBD experiments [5, 6] and references therein. Actually, it has been

shown that solar- ν CC interactions with DBD isotopes like ^{100}Mo , ^{116}Cd and ^{150}Nd can be used for real-time studies of the low-energy solar- ν s [7, 8, 9].

The solar- ν NC and CC interactions with atomic electrons (ν -e scattering) and nuclei in DBD detector are considered. Fig.1 shows the interaction schemes for the CC interactions with the atomic electron and the nucleus. The scattered electron, the electrons (inverse β ray) from the CC interaction, the γ rays following NC and CC interactions, and delayed β rays from the intermediate nucleus B contribute to the BGs if they deposit their energy at the ROI of the $0\nu\beta\beta$ Q value.

Figure 1. Solar- ν CC interaction schemes. Left hand side: Solar- ν CC interaction with an atomic electron in a DBD detector. Right hand side: Solar- ν CC interaction with a nucleus A in a detector. e: scattered electron. W: CC weak boson. p: proton. n: neutron. B: residual nucleus. * indicates a possible excited state in B.



Large scale DBD experiments are under progress and/or in discussion to search for the Majorana ν masses in the IH and NH regions. One discussed option is the usage of large liquid-scintillator detectors loaded with the DBD isotope of interest at the level of some 10^{-2} of the scintillator mass itself or even larger. KamLAND-Zen uses a k-ton liquid scintillator with multi-100 kg ^{136}Xe [10], and SNO+ plans to study ^{130}Te by means of a 0.8 k ton liquid scintillation detector loaded with 0.3 % natural Te (^nTe) [11]. Both consider upgrades in the amount of loaded DBB isotope and other new experiments might follow this idea. Liquid scintillators have also been discussed for possible $\beta\beta$ experiments with ^{100}Mo for the MOON experiment [7, 12] and ^{150}Nd [13] at the beginning of SNO+. The total volume of the detector amounts to k-ton, and larger detectors like JUNO with 20 k-tons are already in preparation and M-ton scales might be necessary for NH mass studies. Given these sizes of detectors, BGs due to solar ν interactions with liquid scintillators have to be considered as well, as already 300 ton scintillation detectors like Borexino operate as solar- ν experiments.

In the previous papers, we evaluated BG contributions of the solar- ν interactions with DBD nuclei [5] and atomic electrons of DBD isotopes [6]. In the latter case an average number of about 1.5×10^{-4} counts/keV per year ton (yt) for all relevant DBD isotopes is expected due to the ^8B - ν interactions. The solar- ν interactions with DBD isotopes were shown to be serious for DBD experiments to search for the IH and NH mass regions, depending on the nuclear matrix element and the energy resolution of the detector at the Q -value [5].

The present paper aims to discuss contributions of the solar- ν interactions with atomic electrons and nuclei involved in large-scale liquid scintillators. This involves the DBD isotope and the scintillator material. Actually the solar- ν BG may set an upper

limit on the DBD detector sensitivity for the $0\nu\beta\beta$ half-life to be measured and thus a lower limit of the sensitivity for the Majorana neutrino mass to be detected.

2. Solar- ν interactions with scintillators

Let us first evaluate event rates of the solar- ν interactions with atomic electrons and nuclei in liquid scintillators to compare them with $0\nu\beta\beta$ rates of current $\beta\beta$ experiments for the IH mass region. The ν -e cross section including CC and NC interactions with atomic electrons is given as [14]

$$\frac{\sigma_e(E)}{dT} = \frac{2G_F^2 m_e}{\pi} [g_L^2 + g_R^2 (1 - \frac{T}{E_\nu})^2 - g_R g_L \frac{m_e T}{E_\nu}], \quad (1)$$

where E_ν is the neutrino energy, T is the electron kinetic energy, G_F is the Fermi constant, $g_L = 0.5 + \sin^2\theta_W$, and $g_R = \sin^2\theta_W = 0.231$. Noting that the $0\nu\beta\beta$ Q -value for the most relevant DBD nuclei of current interest is around 2.5 ± 0.5 MeV, the only solar- ν component to be considered at the ROI is the ^8B - ν flux. The recoil electron yield $b(E)$ as a function of the energy is derived from the cross section $\sigma_e(E)$ and the solar- ν flux $\phi(E)$ corrected for the ν -oscillation effect [6].

We consider a liquid scintillation detector with N' tons of the scintillator and N tons of the DBD isotope dissolved into the scintillator. In most DBD experiments using liquid scintillators, one may assume $N' \gg N$, and thus the ratio is $N/N' \ll 1$. Furthermore we assume a constant detector volume. The neutrino-electron scattering rate at the energy window ΔE of ROI per year per ton (yt) of the DBD isotope is expressed as

$$B_e(E) = 0.6 \times b(E) \frac{Z'}{A'} \frac{E\delta}{R} /yt, \quad (2)$$

where $b(E)$ is the electron yield in unit of 10^{-33} per keV per year per electron in the liquid scintillator, and Z'/A' is the ratio of the number of electrons to that of nucleons in the scintillator, $\delta = \Delta E/E$ stands for the energy resolution and $E = Q$ is the DBD Q value in units of MeV. The energy window ΔE may correspond to the FWHM resolution in units of MeV. The electron to nucleon ratio is $Z'/A' = 50/92$ in case of toluene ($\text{C}_6\text{H}_5\text{CH}_3$) and $Z'/A' = 130/232$ for LAB (assuming an average molecule of $\text{C}_{17}\text{H}_{28}$), respectively. For simplicity $Z'/A' = 0.55$ is chosen.

The energy spectrum of the recoiling electrons is nearly flat as a function of the energy [6] in the region of 2-3 MeV. It is approximately given as $b(E) \approx 0.67 - 0.063E$ with E being the scattered electron energy in units of MeV. Thus the event rate is nearly independent of the DBD Q values, and the rate is given as

$$B_e(E) \approx 0.15 \times E f /yt, \quad (3)$$

where $f = \delta/R$ with $R = N/N'$ being the ratio (concentration) of the DBD isotopes to the scintillator ones. f is a kind of a BG efficiency for the liquid scintillator. As the resolution δ (i.e. ΔE) increases, f and thus $B_e(E)$ increase. As the concentration of the

DBD isotopes decreases, the relative weight of the DBD isotopes decreases and f and $B_e(E)$ relative to the DBD isotope increases. In a typical case of $\delta=5\%$ and $R=1\%$, one gets $f = \delta/R=5$ and $B_e(E) \approx 2-3$ /yt at $E \approx 3$ MeV.

Next we consider the CC interaction on carbon nuclei in the scintillator. The cross section is given as [16]

$$\sigma_C(k) = \frac{G_F^2 \cos^2 \theta_c}{\pi} p_e E_e F(Z, E_e) B_k \text{ cm}^2, \quad (4)$$

where G_F is the Fermi weak coupling constant, θ_c is the Cabibo angle, p_e and E_e are the out-going electron momentum and the total energy in MeV/c and MeV, $F(Z, E_e)$ is the Fermi-function and B_k is the weak strength for the k^{th} state in the intermediate nucleus B (see Fig.1). The strength is written as

$$B_k = B(F)_k + g_A^2 B(GT)_k, \quad (5)$$

where $B(F)_k$ and $B(GT)_k$ are the Fermi and GT strengths, and $g_A = 1.267$ is the axial vector coupling constant in unit of the vector one [15]. The CC cross section can be rewritten as

$$\sigma_C(k) = 1.6 \times 10^{-44} p_e E_e F(Z, E_e) B_k \text{ cm}^2. \quad (6)$$

Since ^{12}C with $Q = -17.338$ MeV cannot be excited by the solar- ν CC interaction, the CC interaction to be considered is the $^8\text{B}-\nu$ CC interaction on ^{13}C with the natural abundance of 1.1%. The interaction is predominantly the ground state ($k = gs$) transition with $Q = -2.220$ and $\log ft = 3.7$. We evaluate the BG rate $B_{gs}(E)$ at $E = Q=3$ MeV of current interest. Then the CC interactions of the $^8\text{B}-\nu$ with the energy around $E_\nu=5.22$ MeV contributes to the BG in the ROI at $E=3$ MeV. Using the CC cross section for $E=3$ MeV and the $^8\text{B}-\nu$ flux at 5.22 MeV taking ν oscillations into account, the BG rate integrated over the energy window of $\Delta E = E\delta$ is of the order of $10^{-3} f E/\text{yt}$. This is much smaller than the BG rate of the ν -e scattering (eq.(3)).

3. Comparison with DBD rate

We now evaluate the $0\nu\beta\beta$ signal rate to compare with the solar- ν BG rates. The $0\nu\beta\beta$ rate per yt for the light Majorana- ν exchange is written as [1, 4]

$$S_{0\nu} = \ln 2 G^{0\nu} (m_{eff})^2 [M^{0\nu}]^2 \epsilon \frac{6 \times 10^{29}}{A} / \text{yt}, \quad (7)$$

where $G^{0\nu}$ is the phase space volume, m_{eff} is the effective Majorana ν -mass in unit of the electron mass, ϵ is the $0\nu\beta\beta$ peak detection efficiency after various on-line and off-line cuts and $M^{0\nu}$ is the nuclear matrix element for the light ν -mass process. Here we note that $G^{0\nu}$ includes conventionally the axial weak coupling $g_A = 1.267 g_V$ with g_V being the vector coupling constant. Then $M^{0\nu}$ is expressed as

$$M^{0\nu} = \left[\frac{g_A^{eff}}{g_A} \right]^2 M_A^{0\nu}(\text{NM}) + \left[\frac{g_V^{eff}}{g_A} \right]^2 M_V^{0\nu}(\text{NM}), \quad (8)$$

where $M_A^{0\nu}(\text{NM})$ and $M_V^{0\nu}(\text{NM})$ are axial-vector and vector components, and g_A^{eff} and g_V^{eff} are the effective axial-vector and vector coupling constants in nuclei. The ratios g_A^{eff}/g_A and g_V^{eff}/g_V stand for the renormalization(quenching) factors due to such non-nucleonic (isobar, exchange current etc) and nuclear medium effects that are not explicitly included in the nuclear matrix components [17, 18]. Actually, the renormalization factor around $g_A^{eff}/g_A \approx 0.5 - 0.6$ is suggested in case of the pnQRPA model due to isobar and other nuclear medium effects [19, 20]).

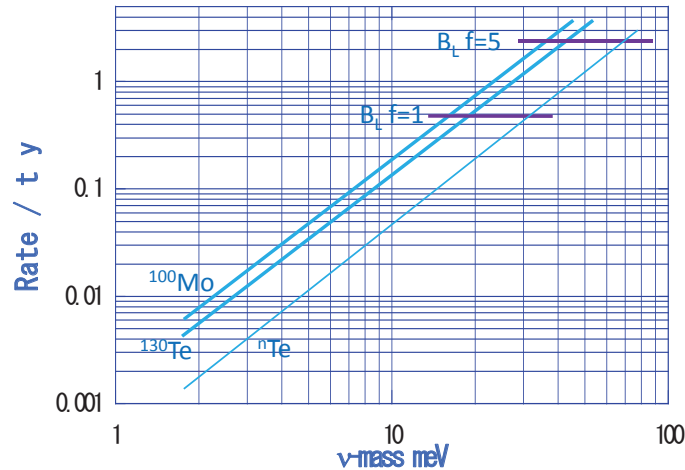
For a typical case of $G^{0\nu} = 5 \times 10^{-14}/\text{y}$, $m_{eff} = 20 \text{ meV}/m_e$, $A=100$, and $\epsilon=0.6$, the $0\nu\beta\beta$ signal rate is

$$S_{0\nu} \approx 0.2 \times (M^{0\nu})^2 / \text{yt}. \quad (9)$$

In the case of a typical $M^{0\nu} \approx 2-3$, the signal rate is an order of $1/\text{yt}$, This is of the same order of magnitude as the solar- ν BG rate for $f \approx 2$ and $E \approx 3 \text{ MeV}$ given in eq.(3).

The $0\nu\beta\beta$ signal rates for ^{100}Mo and ^{130}Te are plotted as a function of the effective ν -mass and are compared with the ν -e scattering BG rates in Fig.2. The DBD signal rate with $M^{0\nu}=2$ for the IH mass of 20 meV is nearly the same as the BG rate for a very ideal case of $f=1$, for example this could be 5 % energy resolution and 5% DBD isotope concentration. In a more realistic case of $f=5$, i.e. 7% resolution and 1.4 % concentration, the BG rate is larger than the signal rate at $m_{eff}=20 \text{ meV}$, and thus it is hard to cover the IH mass region of $15-45 \text{ meV}$.

Figure 2. The $0\nu\beta\beta$ signal rates for $M^{0\nu}=2$, i.e. $S_{0\nu}/s^2$ with $s = M^{0\nu}/2$, as a function of the effective ν -mass m_{eff} and the solar- ν BG rates for ^{100}Mo , ^{130}Te and ^nTe (thin line). Given are the rates per year per ton of ^{100}Mo , ^{130}Te and ^nTe . The solar- ν e scattering BG rates $B_l / \text{y t}$ are shown for $f=1$ and 5 (horizontal lines).



The $0\nu\beta\beta$ rate given in eq.(7) is the rate in case of pure (100% enriched) DBD isotopes. If one uses natural Te (^nTe) isotopes with 34% ^{130}Te , the ^{130}Te $\beta\beta$ signal rate per ton of ^nTe gets smaller by a factor 3 than the rate for the enriched ^{130}Te , while

the solar- ν BG rate remains same, as shown in Fig.2. Accordingly, one needs a liquid scintillator with $f = \delta/R \ll 1$ to cover the IH mass region if $M^{0\nu}$ is around or less than 2, while the requirement is a bit relaxed to $f = \delta/R \ll 2$ if $M^{0\nu}$ is as large as 3.

4. Neutrino mass sensitivity

In order to discuss quantitatively the neutrino mass to be detected in DBD experiments, we introduce the neutrino mass sensitivity m_ν defined as the minimum Majorana ν -mass to be detected by the detector with 90 % confidence level. The minimum mass in unit of MeV is written as [1, 4]

$$m_\nu = \frac{78}{M^{0\nu} G^{1/2} \epsilon^{1/2}} \frac{n^{1/2}}{(NT)^{1/2}} \text{ meV}, \quad (10)$$

where $G = G^{0\nu}/(0.01A)$ with A being the mass number, ϵ is the $0\nu\beta\beta$ peak detection efficiency, as defined before, n is the number of counts required to identify the $0\nu\beta\beta$ peak with 90 % confidence level, and T is the exposure time in units of year. In case of ideal experiments with no BGs, we get $n \approx 2.3$. In practice, the BG rate is so large that one may set $n = 1.7 \times (BNT)^{1/2}$ with B being the BG rate per year per ton of the DBD isotopes [1].

Then the mass sensitivity is rewritten as

$$m_\nu = \frac{m^0 f^{1/4}}{(NT)^{1/4}}, \quad (11)$$

$$m^0 = 102 \times \frac{(0.33 b(E) E)^{1/4}}{M^{0\nu} G^{1/2} \epsilon^{1/2}} \text{ meV}, \quad (12)$$

where m^0 is the unit mass sensitivity in units of meV and $E=Q$ is in units of MeV. This is the sensitivity for $NT=1$ (ton year) and $f=1$, for example $R=10$ % loading and $\delta=10$ % resolution. The background rate $b(E)$ is obtained from the energy spectrum of the scattered electrons [6].

Extensive studies of high-sensitivity DBD experiments are in progress on such DBD nuclei as ^{76}Ge , ^{82}Se , ^{100}Mo , ^{116}Cd , ^{130}Te , and ^{136}Xe [1, 4]. Here we assume the $0\nu\beta\beta$ peak efficiency $\epsilon=0.6$ after various cuts. The m^0 values together with the Q and G values for these DBD nuclei are listed in Table 1.

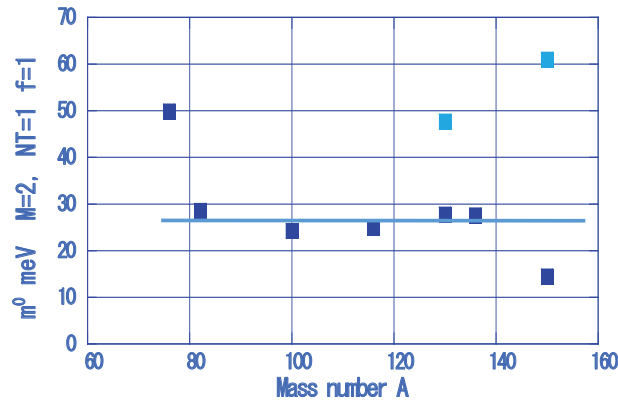
The unit mass sensitivities for DBD nuclei of current interests are plotted in Fig.3. The sensitivities are around 25-30 meV for most DBD nuclei except the cases of ^{76}Ge and ^{150}Nd , where the sensitivities are around 50 meV and 15 meV respectively. The large m^0 value for ^{76}Ge is due to the relatively small phase space of $G^{0\nu}$. However, from the experimental point of view, ^{76}Ge experiments have the best energy resolution.

As an example, the mass sensitivities for ^{130}Te are plotted for three cases of the liquid scintillators with $f = 1, 5$ and 20 in Fig.4. One needs around 50 ton year exposures in cases of $f=5$ to cover the IH mass region of 15-45 meV. The mass sensitivities for other

Table 1. DBD nuclei and the unit mass sensitivities m^0 in units of meV. Q is the $0\nu\beta\beta$ Q value in MeV, $G = G^{0\nu}/(0.01A)$, and $b(E)$ is the BG rate in units of 10^{-33} per year per keV per electron of the liquid scintillator at $E=Q$. The column 5 shows $m^0/(2/M^{0\nu})$, i.e. the unit mass sensitivity for $M^{0\nu}=2$.

Isotope	Q MeV	G $10^{-14}/y$	$b(E)$ /keV/ ye	$m^0/(2/M^{0\nu})$
^{76}Ge	2.039	0.93	0.57	50
^{82}Se	2.998	3.79	0.51	29
^{100}Mo	3.034	5.03	0.50	24
^{116}Cd	2.814	4.69	0.52	25
^{130}Te	2.528	3.76	0.53	28
^{136}Xe	2.468	3.77	0.53	28
^{150}Nd	3.368	15.5	0.53	15

Figure 3. The unit mass sensitivities for DBD nuclei of current interests. The values $m^0/(2/M^{0\nu})$ (dark blue squares), i.e. the unit mass sensitivities m^0 in case of the matrix element $M^{0\nu}=2$ and the 100 % enriched isotope. The values $m^0/r^{1/2}$ (light blue squares) are for natural Te with $r=34\%$ of ^{130}Te and natural Nd with $r=5.6\%$ of ^{150}Nd respectively (see text).



isotopes are nearly the same except ^{76}Ge and ^{150}Nd since the unit mass-sensitivities are nearly the same as shown in Fig.3.

The mass sensitivity given in eq.(10) is for the case of 100 % enriched DBD isotope. In case of DBD isotopes with enrichment r , the $0\nu\beta\beta$ peak efficiency ϵ gets effectively reduced by the factor r and the unit sensitivity is given by $m^0 r^{-1/2}$. DBD isotopes with $r \approx 0.8-0.9$ are used if the centrifugal isotope enrichment is realistic. Then the mass sensitivities are 10-5% larger than the values for the 100% enrichment. The mass sensitivity for the N ton natural Te (^nTe) with ^{130}Te abundance of $r=0.34$ is worse than that for pure ^{130}Te by a factor $r^{-1/2}=1.7$, as shown in Figs. 4 and 5. In order to achieve the same sensitivity as the enriched ^{130}Te , one needs an order of magnitude more isotopes if the exposure time is fixed.

Figure 4. Neutrino mass sensitivities m_ν with $M^{0\nu}=2$ for liquid scintillation detectors with ^{130}Te for three cases of $f=1, 5$ and 20 .

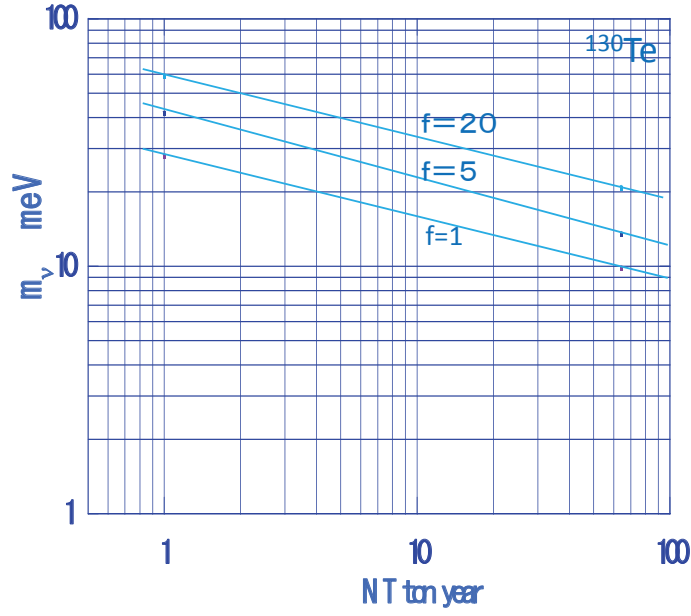
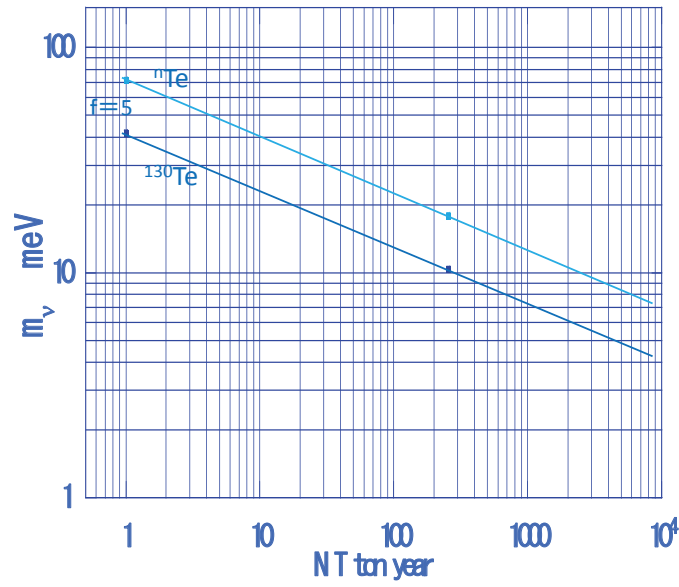


Figure 5. Neutrino mass sensitivities m_ν with $M^{0\nu}=2$ for $f=5$ liquid scintillators with ^{130}Te and ^nTe are plotted as function of the NT yt of ^{130}Te and ^nTe , respectively.



5. Summary

Solar neutrinos interactions with atomic electrons in liquid scintillation detectors used for DBD experiments are evaluated. They are summarized as follows.

1. The BG rate at ROI(region of interest for the $0\nu\beta\beta$ experiment) is given by $B_e(E) \approx 0.15 \times E f$ /y t (year ton), where f is the ratio of the detector energy resolution and the concentration of the DBD isotopes in the scintillator. It is of the same order of magnitude as the $0\nu\beta\beta$ signal rate for the IH ν -mass. So they are serious BG sources for DBD experiments to study the IH ν -mass region.

2. Solar- ν interactions are not avoidable, but their BG contributions are reduced by improving the resolution δ and/or increasing the concentration R . In case of $M^{0\nu} \approx 2$, scintillation detectors with $f \approx 1$ may cover the IH mass of 15-45 meV by the exposure of $NT \approx 10$ ty, but those with $f \approx 5$ require $NT \approx 50$ ty. Then detectors required to cover the NH mass region of $m_\nu = 1.5 - 4$ meV would be 4 orders of magnitude larger in scale than those for the IH mass region, if f would remain the same.

3. It is important to use enriched isotopes, if possible, to increase the signal rate and to decrease the BG rate per ton of the DBD isotopes. In other words, experiments with only a few % abundance of a DBD isotope suffer from large contributions of the solar- ν interactions with atomic electrons and nuclei in other isotopes. Thus they should be enriched to more than 30-50% to cover even the IH ν mass. In case of ^{48}Ca with the natural abundance of 0.2 %, enrichment to around 50 % is crucial although the BG rate $b(E)$ at $Q=4.3$ is lower by 15% than those for other isotopes with $Q \approx 3$ MeV [6].

4. So far we discussed mainly the BG rates from the liquid scintillator with a small concentration of $R \ll 1$. If R is increased to a couple of 10 % in order to improve the mass sensitivity (eq.10), it may affect the resolution δ and increase the BG rate from DBD atomic electrons and nuclei, too. The density change in case of heavy loading may require modifications of the support system of the scintillation apparatus. For example in SNO+ with low loading, ropes have to be fixed at the ground floor, while for massive loading they have to be fixed on the top as the density becomes higher than the surrounding water. Similar issues might be occurring at other experiments as well. Otherwise it could only be compensated by removing scintillator if the volume is fixed. Furthermore it would be a big challenge to reduce the resolution to a few % and to increase the concentration to an order of 10 % simultaneously to realize the small BG efficiency of $f \ll 1$ as required to cover the full IH mass region.

5. The scattered electron is a forward-peak distribution with respect to the incident solar- ν direction. As scintillation detectors also contain a weak contribution of Cerenkov light which is directional sensitive and very fast it might be used, in principle, for rejecting the solar- ν events, but whether it can be done has to be shown.

6. Remarks

Brief remarks on solar neutrino contributions to DBD experiments are given in this section. The BG contributions due to the solar- ν interactions with DBD nuclei should also be well considered in case of liquid scintillators with modest energy resolution of δ . If the BG events involve β, γ , and/or inverse β rays as shown in Fig.1, they might be reduced by measuring their spacial correlations (Signal Selection by Spacial Correlation SSSC) and/or their time correlations (Signal Selection by Time Correlation SSTC) [1, 5]. If not, gamma rays from excited states will add to the background as well.

It should be noted that the mass sensitivity does depend on $M^{0\nu}$. The sensitivities for $M^{0\nu}=2$ as plotted in Figs. 4 and 5 are smaller or larger by a factor 1.3 if the matrix element gets larger or smaller by the same factor. In fact, $M^{0\nu}$ is rather model dependent, and subjects to the uncertainties of the interaction parameters and the renormalization (quenching) of the weak coupling g_A used in the model [4, 17, 18, 19, 20, 21, 22].

In the present letter, we have discussed general features of the solar- ν BG contributions in liquid scintillator DBD experiments, and have evaluated them. The solar- ν ES BGs were also discussed in a review [23]. Actually, they depend on the energy resolution δ (which might change with loading due to changes in optical properties) and the DBD isotope concentration R , and also on the way to reduce the BGs by various hard-ware and analysis cuts. Consequently, the effects of the solar- ν interactions depend largely on details of the individual detector specifications, the configurations and the data-analyses. So we do not discuss the actual rates of the solar- ν BGs for individual current and future detectors.

Finally, we remark that the solar- ν interactions might be potential BG sources for any large-scale experiments to search for low-energy rare events as DBD and dark matter [24, 25], or in turn these detectors could be used for solar neutrino studies as well if $\beta\beta$ and other BGs would be eliminated or separated well.

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